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DIRECT GLASS BONDED HIGH SPECIFIC POWER SILICON SOLAR CELLS FOR SPACE APPLICATIONS

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ABSTRACT

This paper describes a lightweight, radiation-hard, high-performance, ultra-thin silicon solar cell that incorporates light trapping and a cover glass as an integral part of the device. The manufacturing feasibility of high specific power, radiation insensitive, thin silicon solar cells has been demonstrated experimentally and with a model. Ultra-thin, light-trapping structures have been fabricated and the light trapping demonstrated experimentally. Our design utilizes a micro-machined, grooved back surface to increase the optical path length by a factor of 20. This silicon solar cell will be highly tolerant to radiation because the base width is less than 25 microns making it insensitive to reduction in minority-carrier lifetime. Since the silicon is bonded without silicone adhesives, this solar cell will also be insensitive to UV degradation. These solar cells are designed as a form, fit, and function replacement for existing state of the art silicon solar cells with the effect of simultaneously increasing specific power, power/area, and power supply life. Using a 3-mil thick cover glass and a 0.3 g/cm^2 supporting Al honeycomb, a specific power for the solar cell plus cover glass and honeycomb of 80.2 W/Kg is projected. The development of this technology can result in a revolutionary improvement in high survivability silicon solar cell products for space with the potential to displace all existing solar cell technologies for single junction space applications.

INTRODUCTION

The goal of this work was to design and assess the feasibility of lightweight, radiation resistant, high efficiency thin silicon solar cells. This advanced design consists of a 1 mil thick layer of single crystal silicon supported by a 3 mil thick glass superstrate; the glass and silicon are joined using electrostatic bonding (ESB). This novel solar cell design includes several significant advances. These are improved radiation tolerance, increased performance, and high temperature survivability. In the following sections, the advantages of the AstroPower solar cell design are treated in detail.

Radiation Resistance

Radiation damage is the primary degradation mechanism of silicon solar cells deployed in space. This gradual degradation in solar cell performance is due to a reduction in the minority-carrier lifetime that results from cumulative damage to the crystal lattice. One approach to increasing the silicon solar cell radiation tolerance has been to reduce the silicon base thickness as much as possible. Thin silicon solar cells are available in small quantities with current production thicknesses of 2.7 mils and active areas of 59.8 cm^2, however, the best beginning of life efficiencies of these devices are reported to be 14% (ref. 1).

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An opportunity now exists to significantly improve the radiation resistance of silicon solar cells without incurring the yield losses or size limitations of existing thin silicon solar cell technology. The thin silicon solar cell is fabricated by bonding silicon directly to glass, thinning the silicon with a chemical etchant, forming a light trapping structure on the back, and then completing the device fabrication. Before bonding the silicon to the glass coverplate, the emitter and front contacts are formed and the anti-reflection coating is deposited. With this approach, the glass functions as both mechanical support and cover. Device areas will be determined by the cover glass rather than the silicon due to the strength of the glass-silicon laminate. Thin silicon solar cells with an area of over 100 cm^2 are certainly feasible since high quality 6" diameter silicon wafers are readily available.

This novel solar cell design is expected to demonstrate the radiation tolerance observed with InP solar cells. Because the absorber layer is very thin, the solar cell will be extremely insensitive to changes in minority-carrier lifetime that may result from radiation damage. The conversion efficiency of the device will not degrade until the minority-carrier diffusion length is less than the thickness of the absorber layer. For silicon layers on the order of 25 microns or less, this is equivalent to a minority-carrier lifetime of less than 250 nanoseconds (as-grown, non-irradiated silicon typically has a lifetime greater than 10 microseconds). In contrast, to obtain high current, present high-performance silicon solar cells require minority-carrier lifetimes on the order of 1 millisecond. Because this new design effectively reduces the minority-carrier lifetime requirement by more than a factor of one-thousand, this solar cell design leads to an important opportunity for substantially increasing the radiation tolerance, and therefore significantly extending the useful life of silicon solar cells deployed in space.

Modelling and experimental data showing the efficiency degradation of candidate space solar cells as a function of 1 MeV electron fluence is shown in Figure 1. Thin, light trapping, silicon solar cells have theoretical radiation resistance similar to InP space solar cells and better radiation resistance than GaAs/Ge space solar cells. To show the validity of AstroPower's model the experimental and modelled values for a 4 mil thick silicon solar cell are also shown.

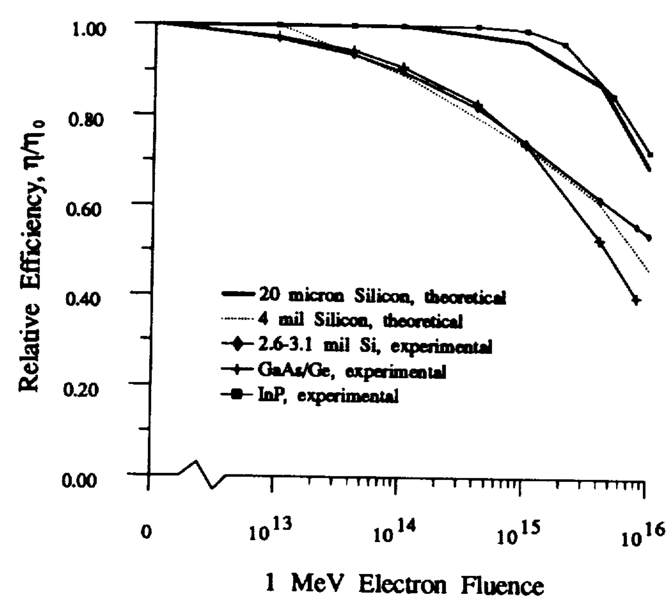

Figure 1. Radiation resistance of space solar cells (ref. 2, 3, 4).

Performance Increase

In addition to radiation resistance, this light-trapping thin base device is also a very high performance silicon solar cell design. After the silicon is thinned, it is micro-machined using an orientation dependent etch to produce a grooved surface. A back surface reflector is then deposited. Using this approach, light that enters the silicon is reflected by the back surface in such a way that it is totally reflected at the planar front surface. It is possible to obtain optical path lengths in thin silicon that approach twenty times the base thickness. Higher open circuit voltages will be achieved because higher than conventional doping levels can be used as a result of the thin silicon solar cell having a reduced dependence on diffusion length. Another increase in the open circuit voltage is due to the smaller recombination volume afforded by the thin solar cell and novel back surface passivation methods. Fill factor improvements can be achieved because low resistivity silicon base layers can be employed in this solar cell design compared to the high resistivity base layers currently in use for silicon space solar cells. The result of these enhancements is that the efficiency of the thin, light trapping solar cell can be as high as 19% and still demonstrate good survivability in the space environment.

The high efficiency and light weight of the cover glass supported silicon solar cell can have a significant impact on space solar array technology. Figure 2 shows the power to weight ratio and power density of several candidate solar

cells. As can be seen, this silicon solar cell design offers an increase in the power to weight ratio over that of a 4 mil, 14.5% efficient silicon solar cell. The power to weight ratio is calculated assuming a 0.3 g/cm² aluminum honeycomb support structure.

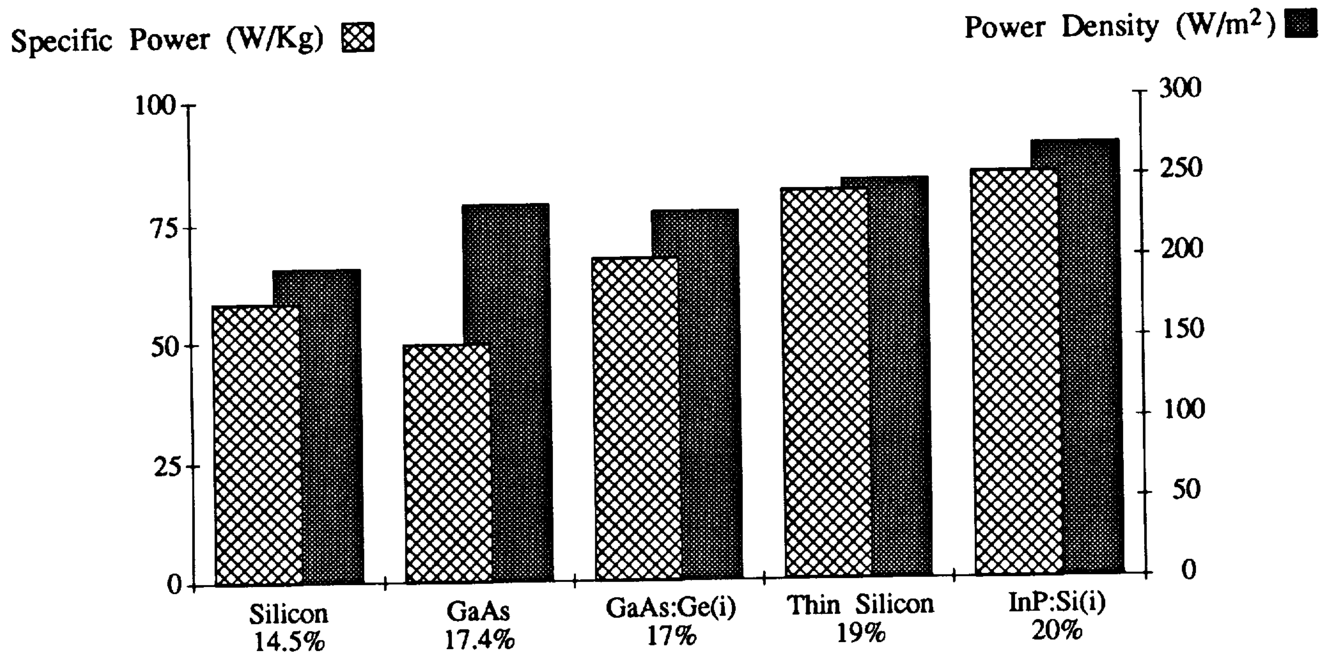

Figure 2. Comparison of specific power and power density of candidate space solar cells.

High Temperature Survivability

Finally, this solar cell is designed with contact metallizations that meet the current Air Force goals for high temperature survivability. After bonding, these devices will retain their insensitivity to high temperatures, permitting the solar cell to be deployed for strategic missions where high temperature survivability and radiation hardness are important considerations.

EXPERIMENTAL RESULTS

A summary of experimental results follows:

- 1 inch x 1 inch, 3 mil thick silicon has been electrostatically bonded to a cover glass;
- 3 mil thick silicon has been thinned to 1 mil while attached to the cover glass;
- light trapping has been accomplished on the 1 mil silicon under glass substrate;
- high temperature survivable contacts have been integrated with the solar cell design;
- a buried contact structure has been developed to present a planar surface to the cover glass for enhanced silicon:glass integrity;
- buried contact solar cells without light trapping have been fabricated and have demonstrated 80.5% fill factors and V_{oc} = 0.606 volts.

A schematic cross-sectional representation of the AstroPower prototype thin silicon solar cell design is shown in Figure 3.

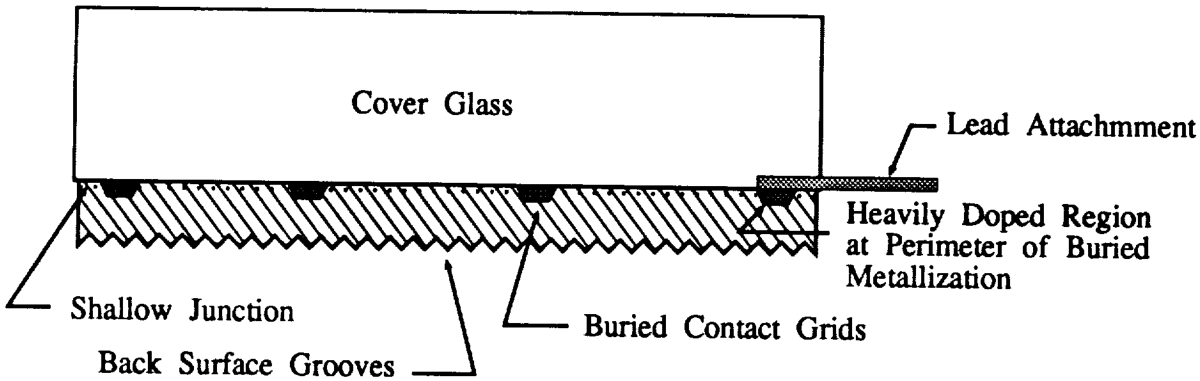

Figure 3. Glass bonded silicon solar cell cross section.

<u>Electrostatic Bonding</u>

A key requirement for successful electrostatic glass-silicon bonding is that the glass cover have the same thermal expansion coefficient as silicon over subsequent process and operating temperature ranges. If a thermal mismatch exists, large residual stresses develop in the structure resulting in fracture of the bond or silicon. A coverglass material specifically designed for electrostatic bonding to silicon has recently been made available (Pilkington CMZ). This glass is thermally matched to silicon over the electrostatic bonding temperature range, has a low deformation temperature enabling intimate contact and complete bonds, and also has a low reaction rate with silver ions migrating from the contact metallization.

The general principles of electrostatic bonding are well known. Heat, pressure, and voltage are applied to the silicon-glass laminate for a short period of time. Typical bonding pressures are on the order of 50 psi, the bonding voltages required are 300V with currents of only a few milliamps, and temperatures of 400°C to 500°C. A lab-scale apparatus for electrostatic bonding silicon to glass and for establishing the time, temperature, pressure, and voltage parameters for successful ESB bonding was fabricated.

A schematic diagram of the lab scale bonding apparatus is shown in Figure 4. This bonder is capable of 1 inch x 1 inch silicon to glass bonding. Using 3 mil silicon and 3 mil Pilkington CMZ cover glass material, a zero void bond was obtained at 400°C with a pressure of approximately 50 psi. The successfully bonded 1 inch x 1 inch silicon under glass structure is featureless confirming the uniformity of the electrostatic bond.

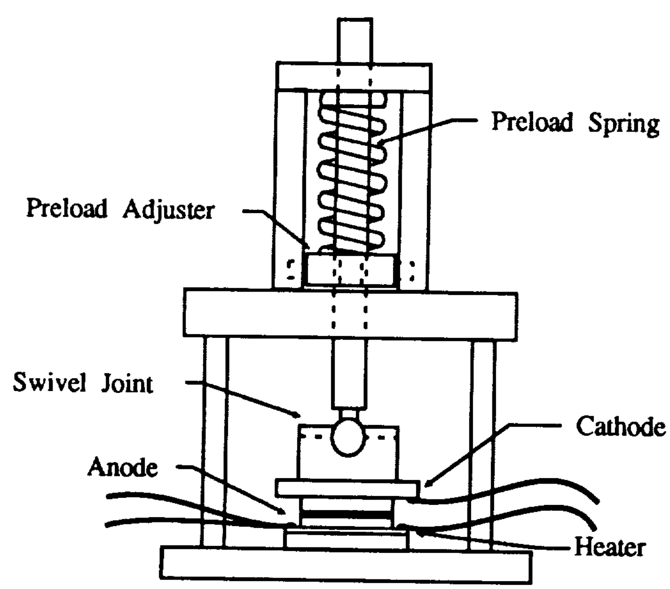

Figure 4. Lab scale electrostatic bonder.

High Temperature Survivable Buried Contacts

Electrostatic bonding of the silicon solar cell to a glass superstrate requires a robust and innovative front contact design. Typically, the metallization utilized by silicon solar cell manufacturers relies on a titanium ohmic contact with a palladium barrier layer and silver plating to achieve low series resistance losses. At the required temperatures inherent to the bonding process, the titanium metal will continue to alloy with the silicon and eventually reach the p/n junction where it will cause a loss in solar cell performance. This loss can be attributed to shunting of the solar cell by the titanium-silicon metal interaction and is not reversible. AstroPower is developing a metallization scheme compatible with the ESB process that avoids this problem and, additionally, permits the silicon solar cell to meet the standards for high temperature survivability.

The high temperature survivable metallization scheme is a plated structure. Choosing a plating method for metallization of the solar cell permits the use of a favorable design option, that is, a buried contact structure. Using a buried contact structure the front surface of the solar cell appears planar to the cover glass during the bonding process and there is no need to use excessive pressure or temperature to deform the glass around surface features,,as there are none. As a second benefit it is cheaper and easier to plate the contact than to use vacuum deposition methods, as is customarily the case with space solar cells, leading to a reduction in the cost of manufacturing.

Light Trapping

In order to obtain high efficiencies from a thin, 25μm, solar cell it is necessary to incorporate a high degree of light trapping in the solar cells. Since the ESB solar cell must have a planar front surface, the light trapping must be achieved by back surface texturing. AstroPower has developed a method to micro-machine the back surface of the silicon solar cell to reflect the photons back towards the front surface at an angle sufficient to permit an equivalent optical thickness up to twenty times the physical thickness. In contrast to a planar back surface reflector, the photons are trapped until they are absorbed by the silicon. With a planar back surface reflector, the photons would make only two passes through the silicon and then escape through the front surface of the solar cell.

Curves of absorption normalized for front surface reflection, Figure 5, of various thicknesses of bonded silicon under glass demonstrate the effectiveness of the micro-machined back surface reflector (BSR). An 8 mil glass bonded silicon sample is included for reference. Note that the light trapping structure with the Al reflector matches the 8 mil reference curve up to 850 nm. Beyond 850 nm it differs by only 5% at the most. The cross-over of the absorbtion curve at 1025 nm is caused by a combination of factors involving non-optimized light trapping in the thin silicon and the low absorbtion co-efficient of narrow bandgap photons in the 8 mil sample. This data clearly shows light trapping in a 33 μm thick silicon sample using back surface grooving and a back surface reflector.

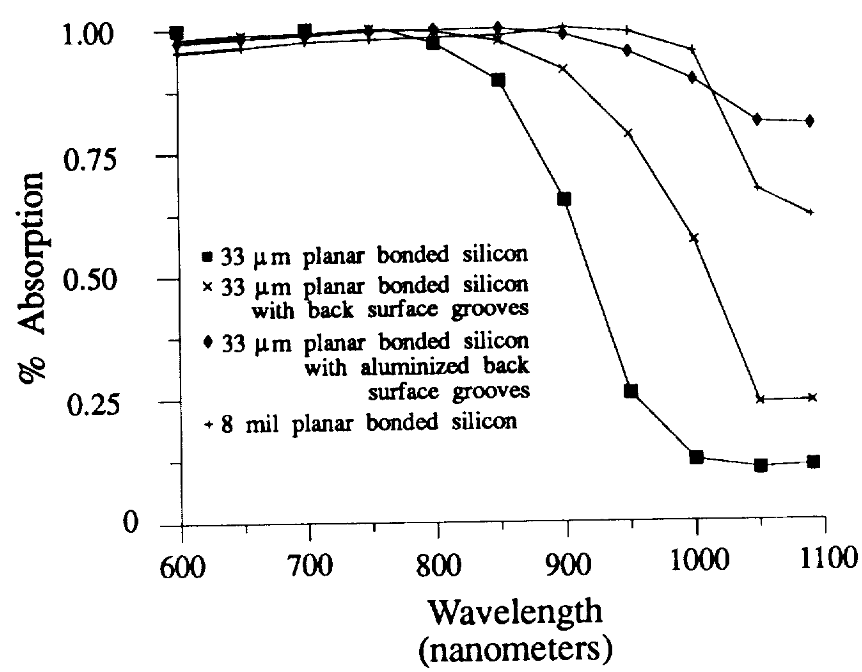

Figure 5. Optical characteristics of thin silicon compared to thick silicon.

CONCLUSION

This work demonstrates the feasibility of the key steps that will be required to produce high specific power, radiation tolerant, thin silicon solar cells. These solar cells will be a form, fit, and function replacement for existing state of the art silicon solar cells with the effect of simultaneously increasing specific power, power density, and power supply life. Followiing is a summary of the necessary processes which when integrated will lead to production of the thin silicon solar cell.

Cover glasses are usually attached to solar cells using an adhesive, which adds weight and eventually degrades and darkens under UV radiation. Electrostatic bonding permits attachment of the silicon to the glass without any intermediate adhesives, provides a permanent chemical bond that adds no weight other than that of the cover glass, and is insensitive to UV degradation. Successful electrostatic bonding of glass to silicon has been achieved on 1 inch x 1 inch, 3 mil thick silicon solar cell substrates.

Although thin silicon solar cells are highly desirable for many reasons already discussed in detail, thicknesses are process limited. The availability of the demonstrated glass:silicon solar cell laminate side steps this issue because the glass:silicon laminate is robust. Silicon attached to the glass by electrostatic bonding can be thinned to any desired thickness. The ability to uniformly thin the silicon has been demonstrated.

Thin silicon is a poor absorber of photons and therefore it is necessary to develop techniques to trap the light in the silicon until it can be absorbed. Micro-machining of the back surface reflector has been achieved and light trapping has been demonstrated.

The electrostatic bonding process requires intimate contact between the cover glass and the silicon to which it is to be bonded. Typical front contact grid metallization designs inhibit this contact. Previous work with electrostatic bonding has shown that the glass can be made to deform over the front contact metallization. The problem with this is that the bond must be made at higher temperatures, near the softening point of the glass, or as has been demonstrated by other researchers, the cover glass can have grooves machined to fit over the metallization. Neither of these solutions is desirable for reasons detailed in the next two paragraphs.

Bonding at temperatures near the softening point of the glass can create stress in the laminate which will lead to lower yields due to breakage. Also the thermal expansion of the cover glass begins to change abrubtly away from that of silicon at 600°C which may inhibit bonding.

Machining of grooves in the cover glass introduces an undesirable cost in the manufacturing of thin silicon solar cells. Not only does the base cost of the cover glass increase but a step must be added to the fabrication process to insure proper alignment of the solar cell grids and the cover glass grooves. Secondly, there are areas of unbonded silicon near the grid structure because the glass machining can not be perfectly matched to the grid. These unbonded areas may lead to stressing in the silicon and certainly will decrease the overall strength of the glass:silicon laminate.

The AstroPower solution to this problem is to bury the contacts in the silicon therefore presenting a planar surface to the cover glass for the electrostatic bonding process. Silicon solar cells have been fabricated with buried contact metallization. Efficiency of these solar cells is greater than 12% with the design capability to reach greater than 18% with process improvement.

During the electrostatic bonding process the solar cell front contact metallization will be exposed to temperatures greater than 400°C. Typically, the metallization used by silicon solar cell manufacturers relies on an alloyed titanium ohmic contact. At the bonding temperatures the titanium metal will continue to alloy and reach the solar cell p/n junction where it will degrade performance. In order to avoid this problem a plated contact system is being developed which is expected to be 700°C survivable for at least 15 minutes. This meets the long term SDI and Air Force goals for high temperature survivability.

The integration of these accomplishments with process improvement, scale up of the solar cell active area, and back surface passivation will result in a demonstration of the manufacturability of this innovative solar cell. A specific power of 80.2 W/Kg and efficiencies of 19%, AM0, are predicted for this thin silicon solar cell design.

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